Higgs and flavour constraints in 2HDM

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Based on arXiv:1706.07414 (EPJC) with A. Arbey, O. Stål and T. Stefaniak

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To the memory of Maria

Moriond QCD, March 30, 2017

Why Two Higgs Doublet Model?

- No reason for the scalar sector to be minimal
- New sources of CP violation
- Candidate for dark matter
- UV complete new physics scenarios usually require additional scalar Higgs states.

- Two major constraints to go beyond the SM:

  $\rightarrow$ The electroweak ρ parameter

  $\rightarrow$ Limits on the FCNCs
- Both naturally satisfied in models with two Higgs doublets

General 2HDM

The Standard Model with two Higgs doublets Φ_1 and Φ_2 with hypercharge $Y = +1/2$

$$V_{\rm 2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$
$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \left\{ \tfrac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.} \right\},$$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v \cos\beta + \phi_1^0\right) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}\left(v \sin\beta + \phi_2^0\right) \end{pmatrix}$$

Yukawa couplings:

$$-\mathcal{L}_{\rm Yuk} = \sum_{i=1}^{2} \left[\overline{Q}_L i\sigma_2 \Phi_i \eta_i^U U_R + \overline{Q}_L \Phi_i \eta_i^D D_R + \overline{L}_L \Phi_i \eta_i^L E_R + \text{h.c.} \right],$$

η_i^F: Yukawa matrices in flavour space

In general, the fermions couple to both doublets, leading to FCNCs.

To avoid FCNCs, a Z_2 symmetry is imposed so that within a family all fermions couple only to one of the doublets.

Two-Higgs Doublet Models with Z_2 symmetry

Type I: one Higgs doublet provides masses to all fermions (up and down-type quarks, and leptons) ($\sim$SM).

Type II: one Higgs doublet provides masses for up-type quarks and the other for down-type quarks and leptons ($\sim$MSSM).

Type III (Flipped): one doublet couples to up-type quarks and leptons, while the other couples to down-type quarks.

Type IV (Lepton Specific): one doublet couples to quarks and the other to leptons.

The Higgs phenomenology depends strongly on the type of Yukawa sector.

Neutral Higgs couplings

	Type I	Type II	Type III	Type IV
g_{huu}	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
g_{hdd}	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
$g_{h\ell\ell}$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
g_{hVV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
g_{Huu}	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
g_{Hdd}	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
$g_{H\ell\ell}$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
g_{HVV}	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
g_{Auu}	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
g_{Add}	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$
$g_{A\ell\ell}$	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
g_{AVV}	0	0	0	0

α: CP-even Higgs mixing angle

Remark: $\sin(\beta-\alpha)=1$ leads to SM-like couplings for the light Higgs at leading order

Charged Higgs couplings

Charged Higgs couplings to fermions: $-ig_{H^+\bar{f}f'}$, with:

$$g_{H^+\bar{U}D} = \frac{V_{UD}}{\sqrt{2}M_W}\left[\lambda_{UU}\frac{1-\gamma_5}{2} + \lambda_{DD}\frac{1+\gamma_5}{2}\right]$$

$$g_{H^+\bar{\nu}_L L} = \frac{1}{\sqrt{2}M_W}\lambda_{LL}\frac{1+\gamma_5}{2}$$

For the different 2HDM types:

Type	λ_{UU}	λ_{DD}	λ_{LL}
I	$\cot\beta$	$\cot\beta$	$\cot\beta$
II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
III	$\cot\beta$	$-\tan\beta$	$\cot\beta$
IV	$\cot\beta$	$\cot\beta$	$-\tan\beta$

Set-up

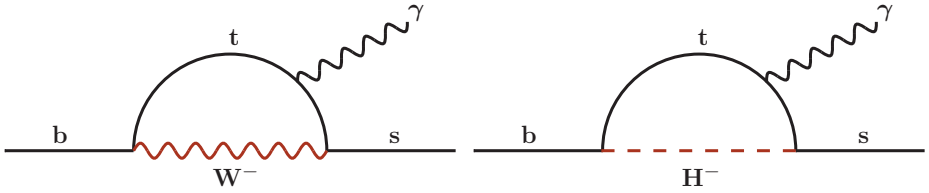
For each 2HDM type there are seven free parameters, which are in the physical basis:

- M_h, M_H, M_A, M_{H^+}, masses of the Higgs states,
- $\tan\beta$, ratio of the Higgs doublet vevs,
- $\sin(\beta - \alpha)$, where α is the mixing angle of the CP-even Higgs states,
- m_{12}, non-diagonal term of the mass matrix of the Higgs doublets.

Codes used for this analysis:

- 2HDMC v1.7.0 (D. Eriksson, J. Rathsman, O. Stål, arXiv:0902.0851)
- SuperIso v3.7 (F. Mahmoudi, arXiv:0710.2067, arXiv:0808.3144)
- HiggsBounds v5.1.0 (P. Bechtle et al., arXiv:0811.4169, arXiv:1311.0055)
- HiggsSignals v2.1.0 (P. Bechtle et al., arXiv:1305.1933, 1403.1582)

Inclusive branching ratio of $\bar{B} \to X_s\gamma$



- Charged Higgs loop always adds constructively to the SM penguin
- SM and 2HDM contributions known to NNLO accuracy (Misiak et al.)

  SM prediction: $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.34 \pm 0.22) \times 10^{-4}$
  Experimental values (HFAG 2016): $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.32 \pm 0.15) \times 10^{-4}$

- Provides the strongest indirect constraints in 2HDM

But Also:

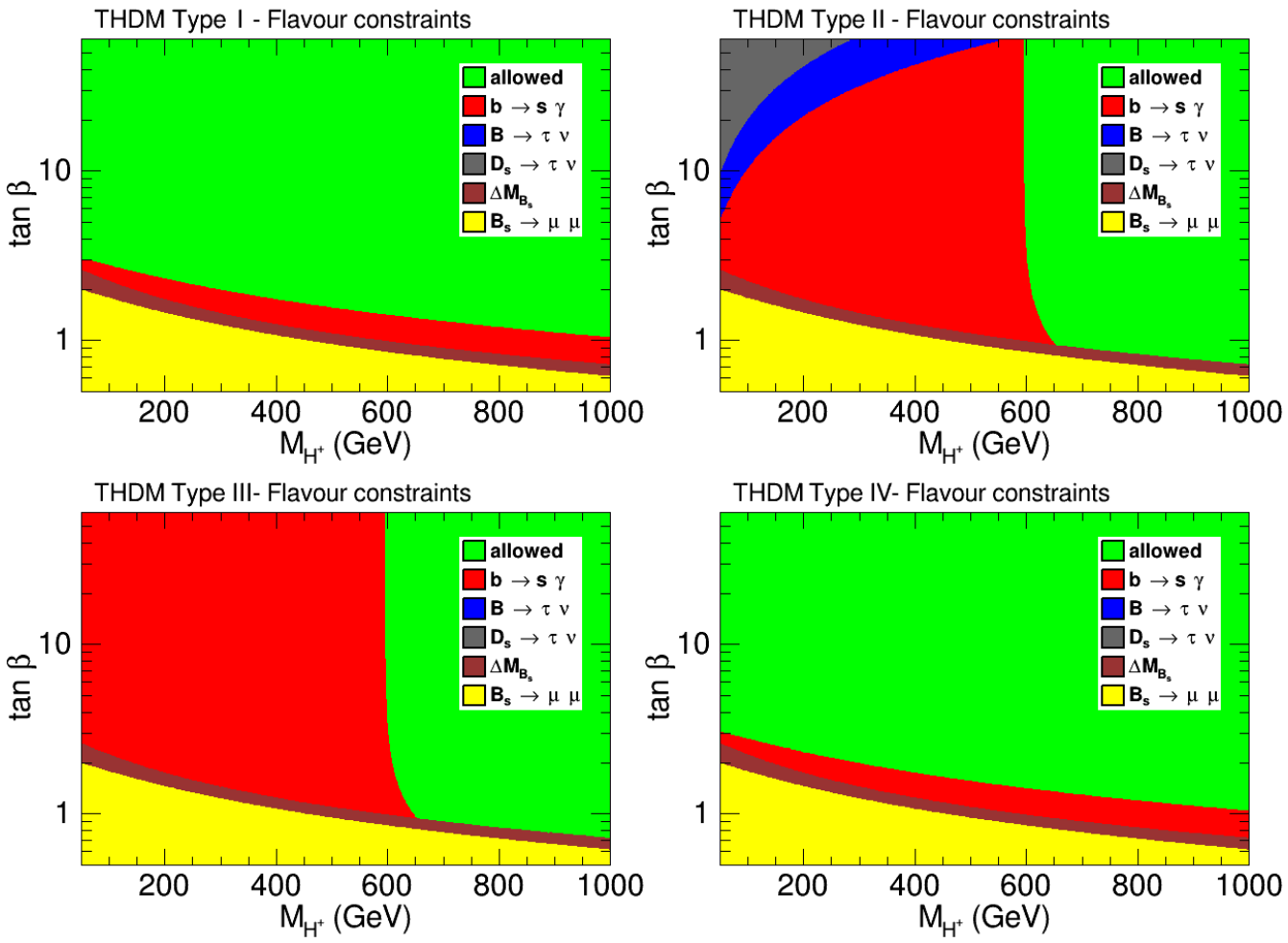
$\Delta_0(B \to K^*\gamma)$, **BR**$(B_s \to \mu^+\mu^-)$, **BR**$(B_u \to \tau\nu)$, **BR**$(D_s \to \tau\nu)$, ΔM_{B_s}

And:

Angular observables and branching ratios of $B \to K\ell^+\ell^-$, $B \to K^*\ell^+\ell^-$, $B_s \to \phi\mu^+\mu^-$

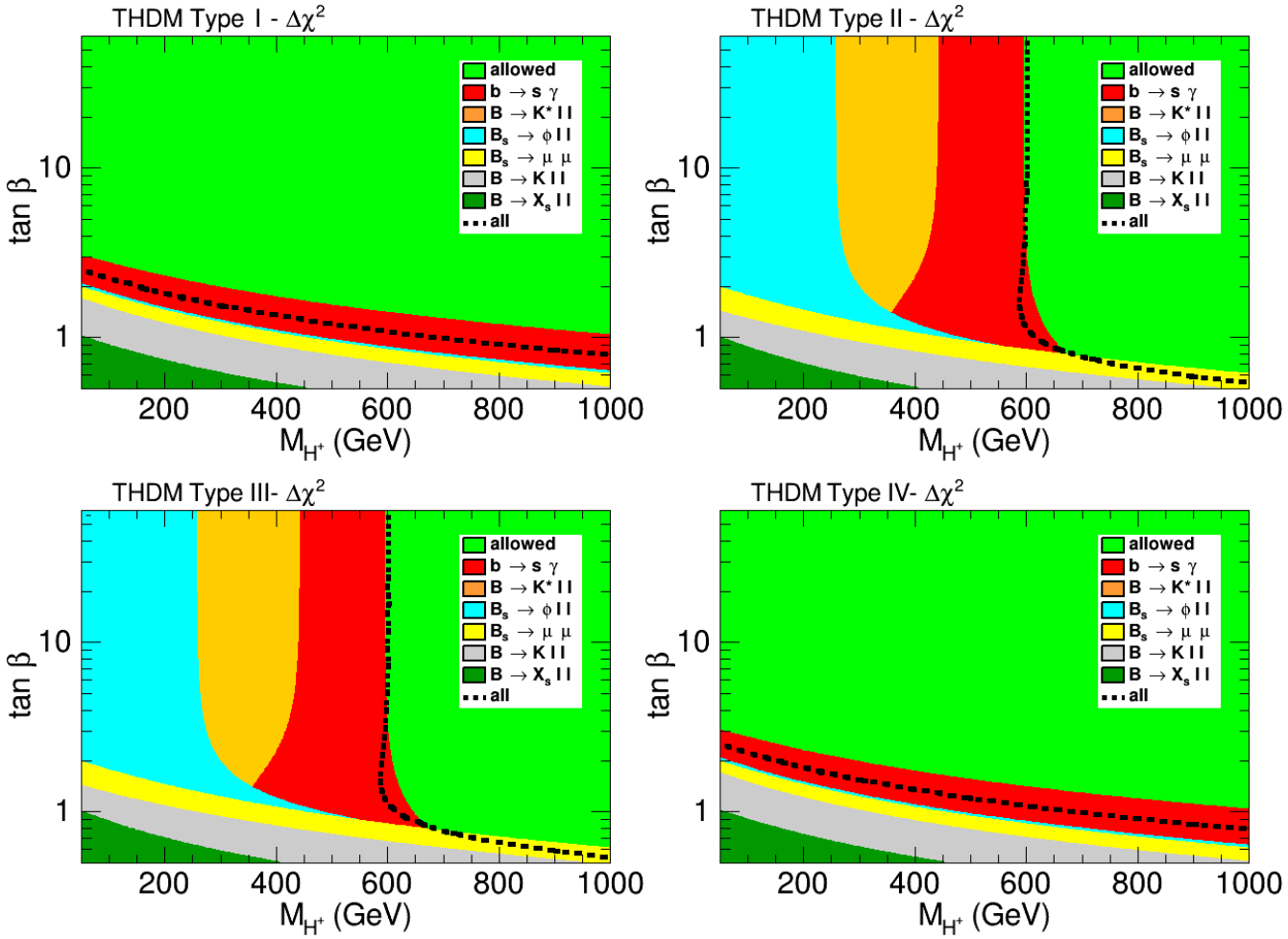
$\to$ Global fit to all available data

Constraints from individual (conventional) flavour observables



Contours corresponding to 95% C.L.

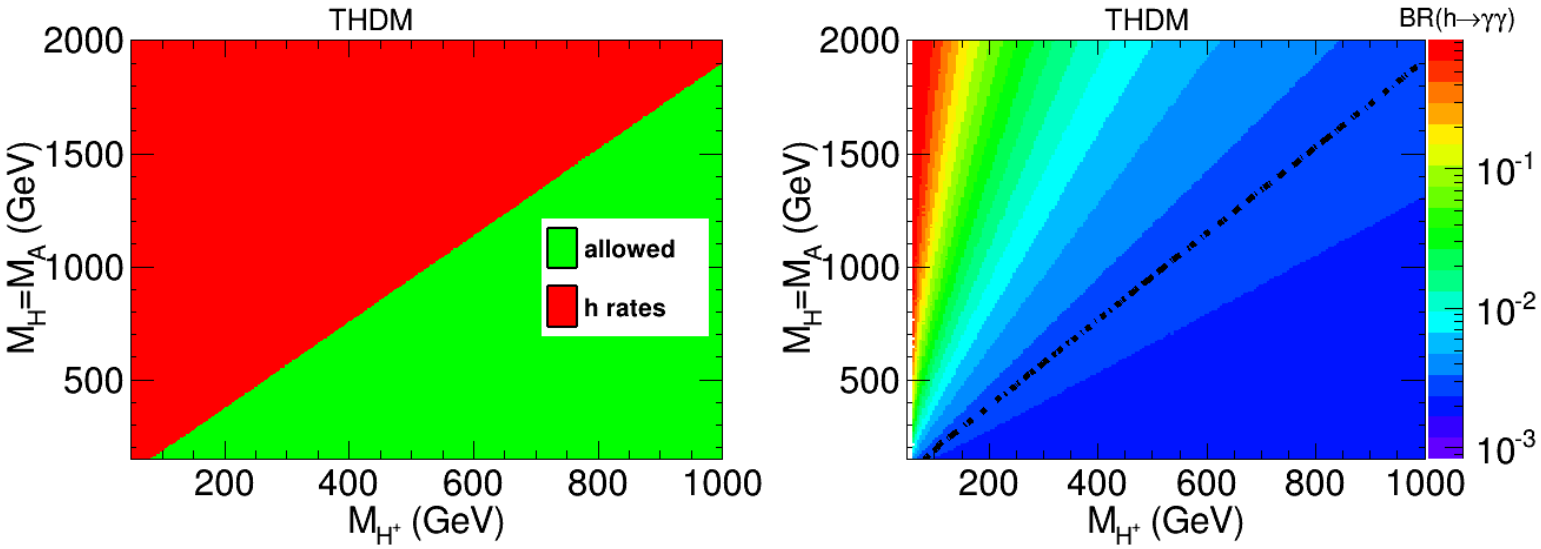
Constraints from $b \to s\ell\ell$ observables



Contours corresponding to 95% C.L.

Constraints from the signal strength measurements of the 125 GeV Higgs:

Example: $\tan\beta = 10$, $\sin(\beta - \alpha) = 1$



Because $\sin(\beta - \alpha) = 1$, the light Higgs couplings are SM-like at tree level.

However, BR($h \to \gamma\gamma$) receives contributions from charged Higgs loop with couplings enhanced for large neutral Higgs masses.

Therefore constraints can be set on the heavy Higgs masses.

Direct constraints

- **LEP**

  Charged Higgs searches: $e^+e^- \to \gamma/Z \to H^+H^-$

  - Combined LEP limits for the $\tau\nu$ and cs final states,
  - The OPAL limit for the $W^\pm h$ final state

  Neutral Higgs searches superseded by LHC searches

- **LHC**

  Charged Higgs searches: $t \to H^+ b$ and $H^- \to \tau\nu, \bar{c}s, \bar{t}b$

  Neutral Higgs searches:

  - Non-standard Higgs decays to $\tau\tau$, $b\bar{b}$, $t\bar{t}$, $\mu\mu$, $\gamma\gamma$, WW, ZZ.
  - Also channels with the SM-like Higgs boson in the final state: $h_{\rm SM}h_{\rm SM}$ and $h_{\rm SM}Z$, with various decay modes of $h_{\rm SM}$.
  - Searches for processes involving two non-standard Higgs bosons (CMS): $H \to AZ$ or $A \to HZ$
  - SM-like Higgs bosons decaying into lighter Higgs states, $h_{\rm SM} \to hh$.

Direct constraints: 2HDM scenarios

Let us consider five different illustrative scenarios:

(a) ***MSSM-like regime***: two free parameters, M_{H^+} and $\tan\beta$, imposing

$$M_H = M_A = \max(M_h, M_{H^+}) \ , \quad M_h = 125.09 \ \mathrm{GeV} \ , \quad \sin(\beta - \alpha) = 1 \ ,$$

(b) ***Heavy neutral Higgs bosons***: two free parameters, M_{H^+} and $\tan\beta$, imposing

$$M_H = M_A = 1 \ \mathrm{TeV} \ , \quad M_h = 125.09 \ \mathrm{GeV} \ , \quad \sin(\beta - \alpha) = 1 \ ,$$

(c) ***Decoupling regime***: three free parameters, M_{H^+}, M_H and $\tan\beta$, imposing

$$M_H > \max(M_h, M_{H^+}) \ , \quad M_h = 125.09 \ \mathrm{GeV} \ , \quad M_A = M_{H^+} \ ,$$
$$\cos(\beta - \alpha) = 0.1 \times (150 \ \mathrm{GeV}/M_H)^2 \ ,$$

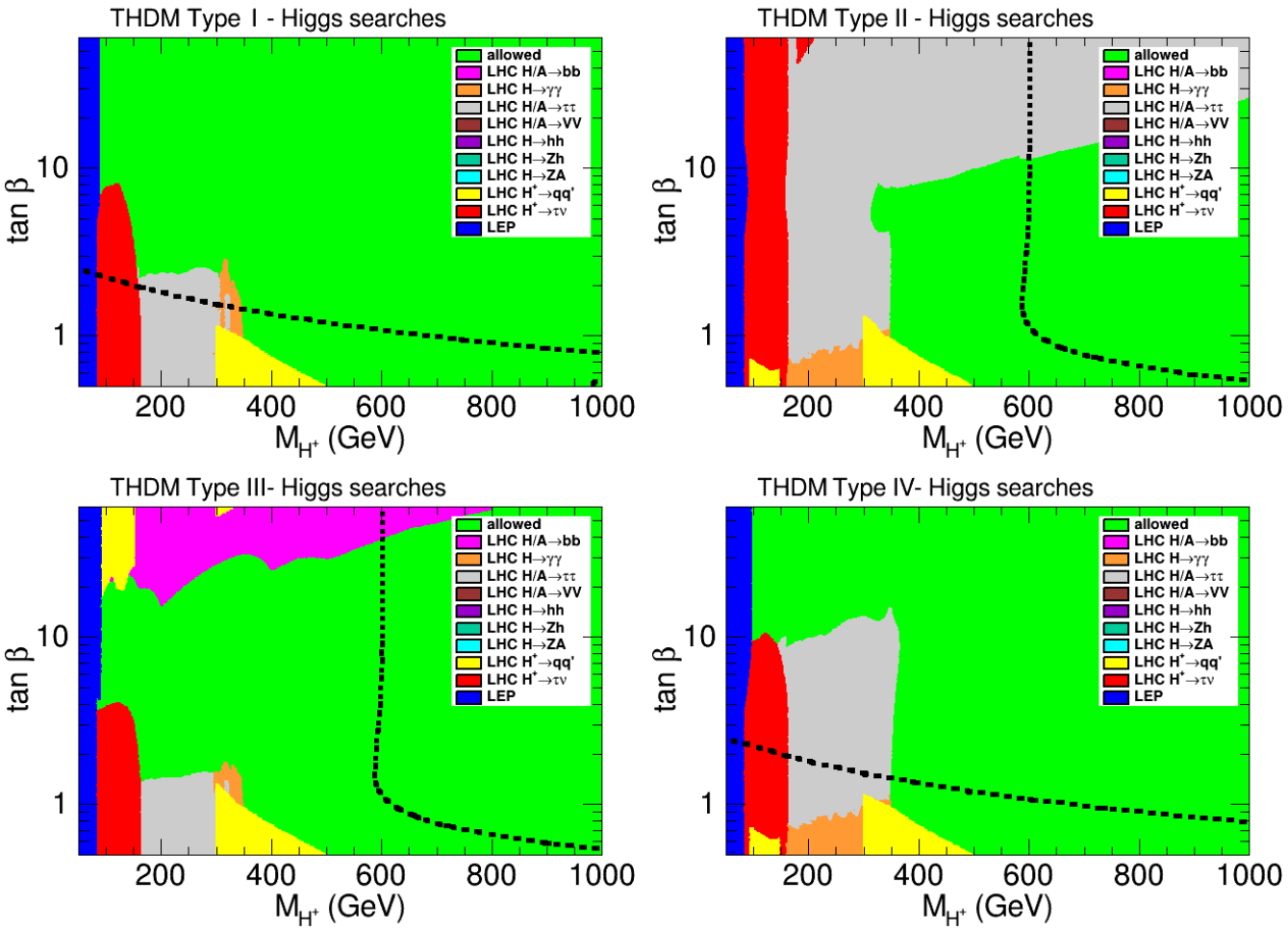
(d) ***General scenario***: only set the light Higgs mass to $M_h = 125.09 \ \mathrm{GeV}$ and vary the six remaining parameters, M_H^+, M_H, M_A, $\sin(\beta - \alpha)$, $\tan\beta$ and m_{12}^2, imposing $M_H > M_h$. This is the most general scenario based on the assumption that the light Higgs state is the observed Higgs state.

(e) ***Inverted scenario***: four parameters M_{H^+}, M_h, $\tan\beta$ and m_{12}^2, assuming

$$M_H = 125.09 \ \mathrm{GeV} \ , \quad \sin(\beta - \alpha) = 0 \ , \quad M_A = M_{H^+} \ .$$

Thus, the heavy CP-even Higgs boson H is assumed to be the observed Higgs state

Scenario (a) (*MSSM-like scenario*)



$M_{H^+} = M_A = M_H$ and $\tan\beta$ only free parameters

LEP searches provide a robust limit for small $M_{H^\pm}$.

Small $\tan\beta$ region mainly probed by charged Higgs searches and $H/A \to \tau\tau$.

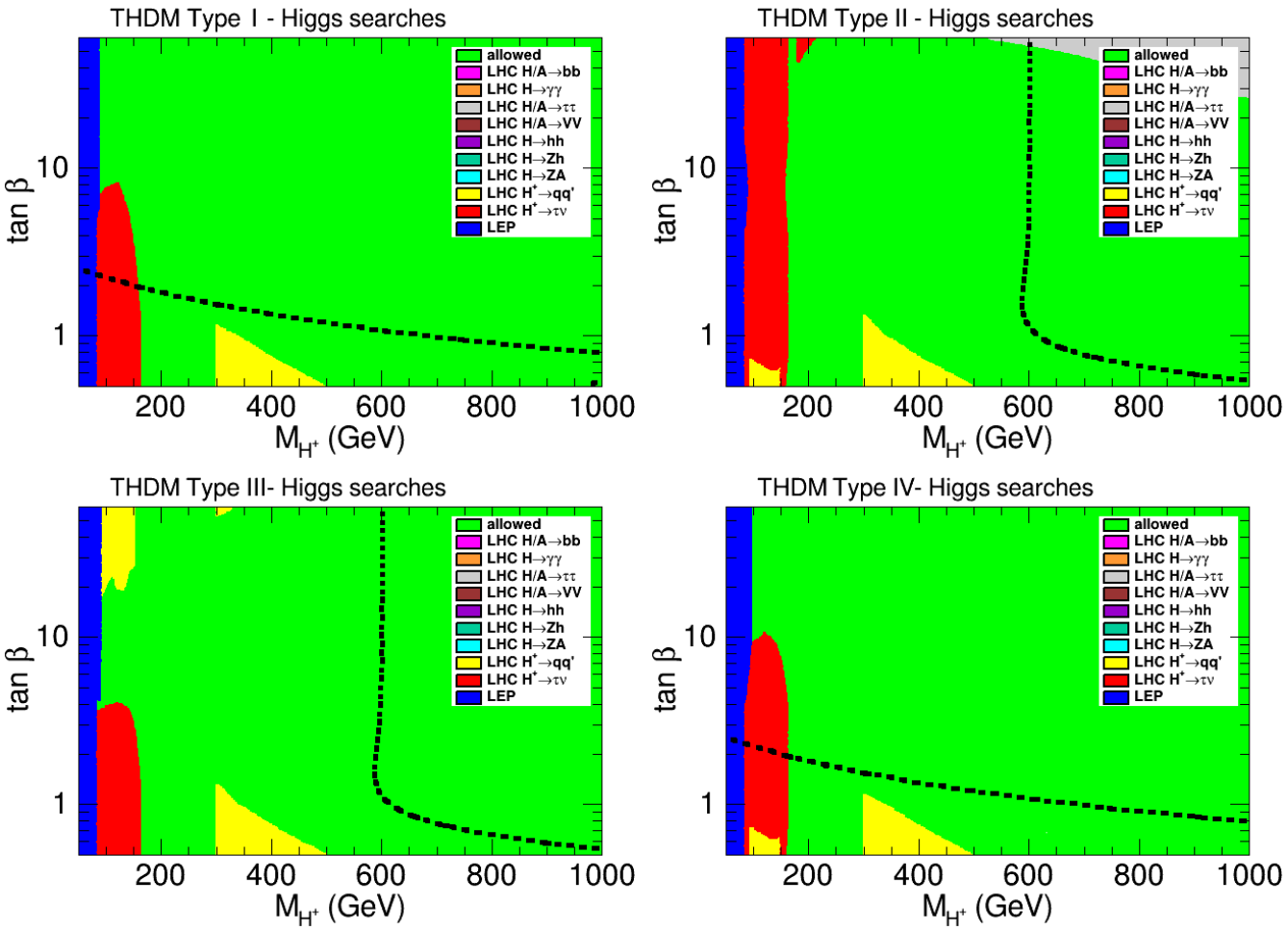
Large $\tan\beta$ region probed only for Types II and III by $H/A \to \tau\tau$ and $H/A \to bb$ searches, respectively.

Exclusions at 95% C.L. by charged and neutral Higgs searches

Green region consistent with all collider constraints

Dotted line: combined limit from all flavour observables.

Scenario (b) (*heavy neutral Higgs bosons*)



M_{H^+} and $\tan\beta$ only free parameters

$M_A = M_H = 1$ TeV set to simulate large-mass decoupling

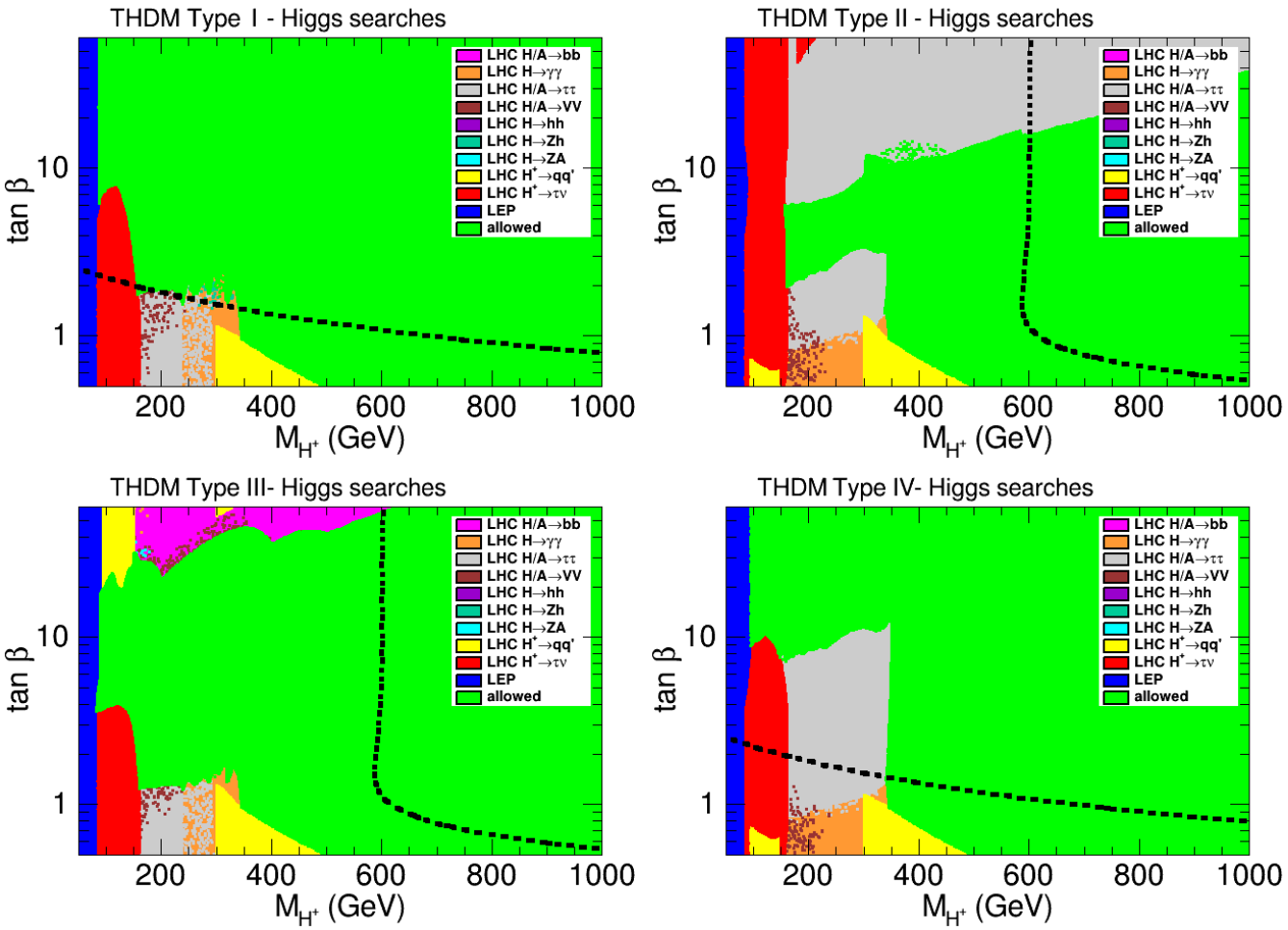
Neutral Higgs constraints strongly affected, mostly charged Higgs searches probe this scenario.

Exclusions at 95% C.L. by charged and neutral Higgs searches

Green region consistent with all collider constraints

Dotted line: combined limit from all flavour observables.

Scenario (c) (*decoupling regime*)



M_H, $M_{H^+} = M_A$ and $\tan\beta$ free parameters

$\cos(\beta - \alpha)$ chosen to emulate weak-coupling decoupling

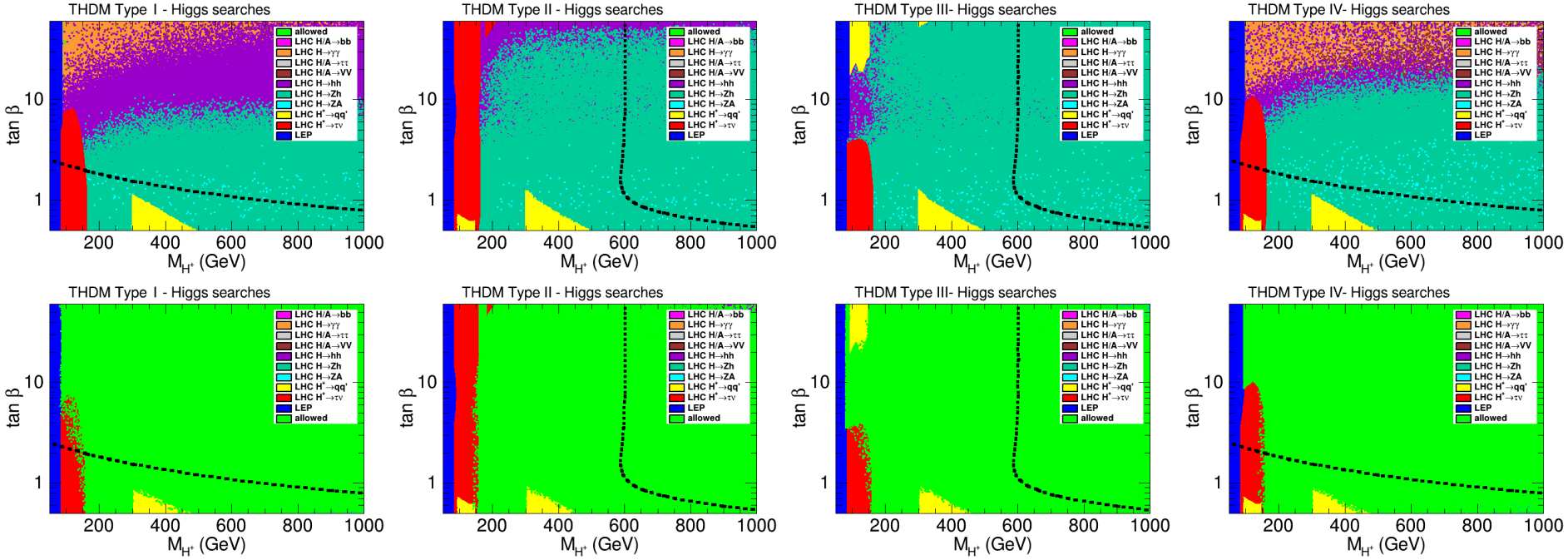
Results rather similar to scenario (a), neutral Higgs searches affected through the independent variation of M_H.

Exclusions at 95% C.L. by charged and neutral Higgs searches

Green region consistent with all collider constraints

Dotted line: combined limit from all flavour observables.

Scenario (d) (*general scenario*)

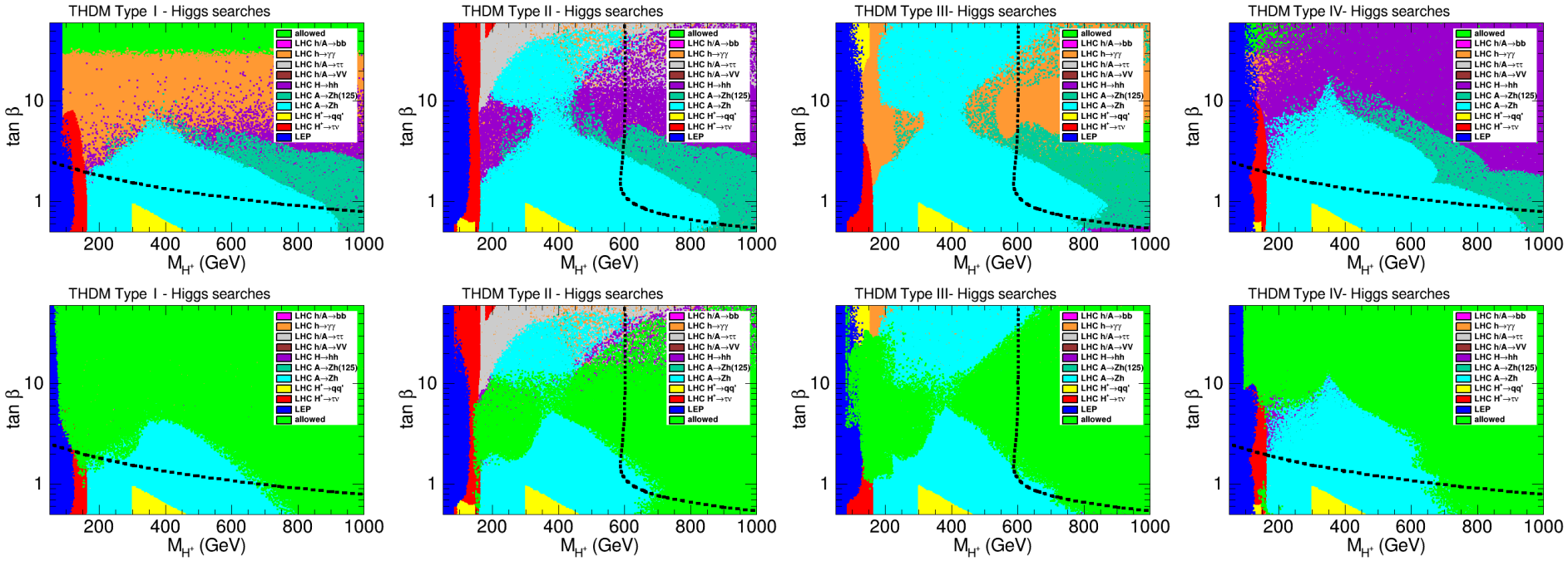


Exclusion at 95% C.L. by charged and neutral Higgs searches.
The points consistent with all collider constraints are shown in the background in the upper panels, and in the foreground in the lower panels.
The dotted line shows the combined limit from all flavour observables.

The different searches play a role and are complementary.

Still many points can escape the neutral Higgs constraints.

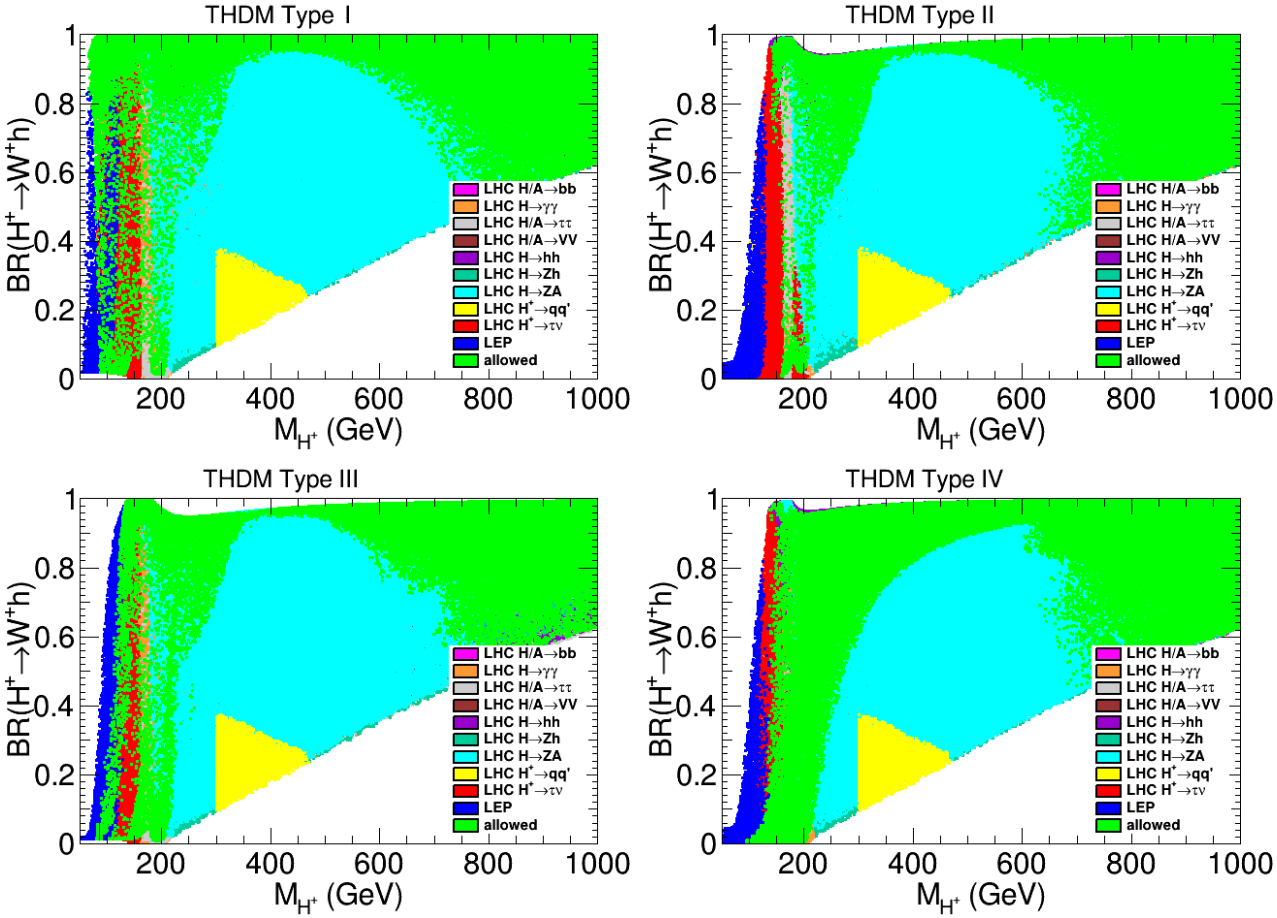
Scenario (e) (Inverted)



Exclusion by Higgs searches at 95% C.L. for the different 2HDM Yukawa types in the inverted scenario (e) where $M_H = 125.09$ GeV and $\cos(\beta - \alpha) = 1$.
Allowed points in background (upper panels), and in foreground (lower panels).
The dotted line shows the constraints from all $b \to s$ observables.

Additional LEP constraints from $e^+e^- \to hA$, with h and A light enough to be kinematically accessible

$H^\pm \to W^\pm h$



$M_H = 125.09$ GeV,
$\cos(\beta - \alpha) = 1$

Large regions with $\mathrm{BR}(H^\pm \to W^\pm h) \sim 1$ not probed by any search.

Exclusions at 95% C.L. by charged and neutral Higgs searches

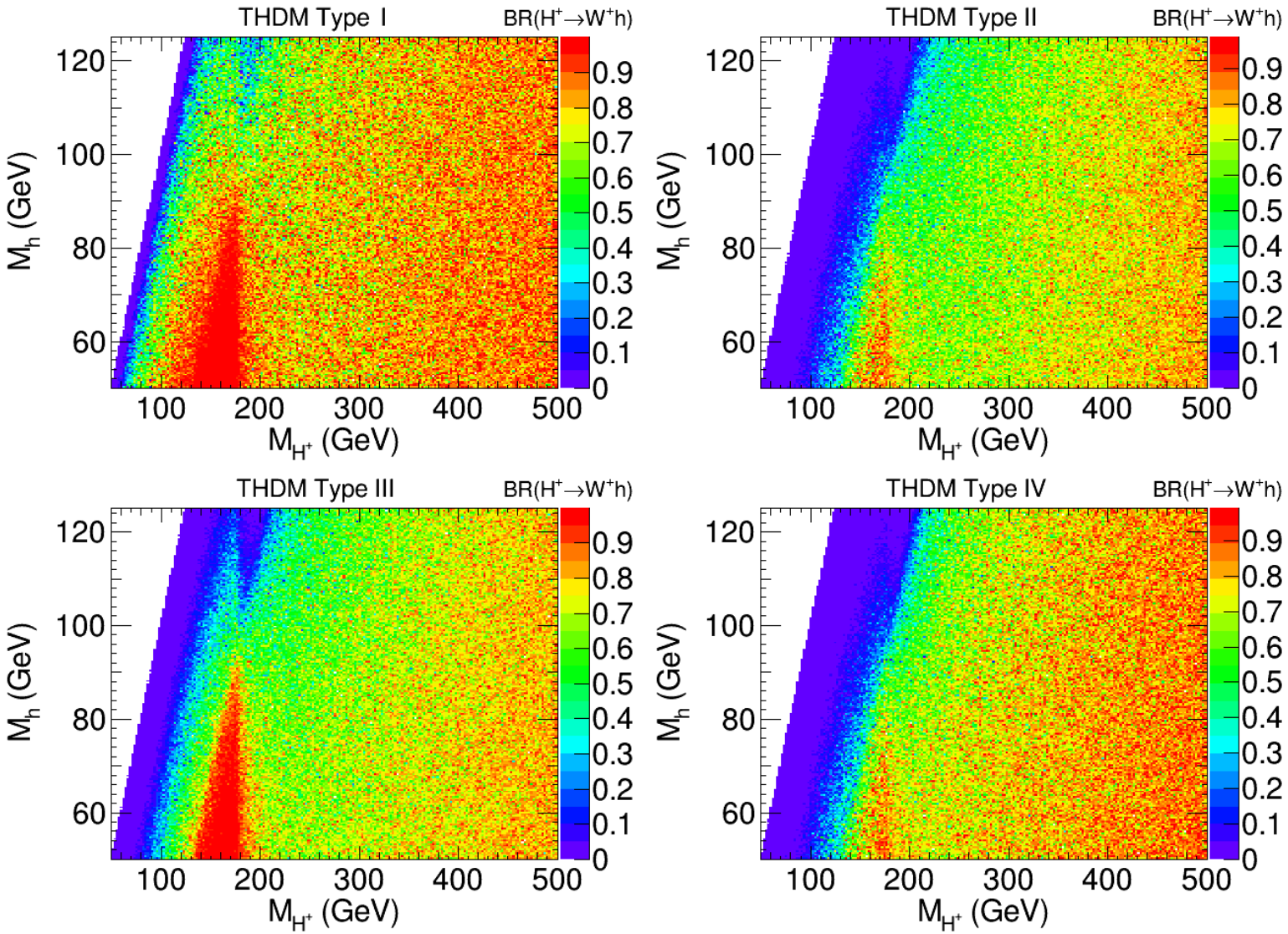
Green region consistent with all collider constraints

Conclusion

- 2HDM is still far from being completely probed at the LHC, even for light Higgs masses
- Limits from charged Higgs searches are very robust with respect to variation of the 2HDM parameters
- A dedicated search for the process $H^{\pm} \to W^{\pm} h$, with the $H^{\pm}$ either produced in top quark decays, or directly in association with a top- and bottom quark, and the h decaying into either bb or $\tau\tau$.
- Neutral Higgs searches give important constraints on the parameter space
- But the constraints from neutral Higgs searches strongly vary among the scenarios, and thus do not provide model-independent limits
- Flavour physics observables provide very strong constraints, which depend (to very good approximation) only on M_{H^+} and $\tan\beta$

Backup

$H^{\pm} \to W^{\pm} h$



Branching fraction of the charged Higgs boson decay $H^{\pm} \to W^{\pm} h$ in the (M_{H^+}, M_h) parameter plane, for the different 2HDM Yukawa types in the inverted scenario **(e)** where $M_H = 125.09$ GeV and $\cos(\beta - \alpha) = 1$.

Flavour constraints

Observable	Experiment	SM prediction
$\mathrm{BR}(B \to X_s\gamma)$	$(3.32 \pm 0.15) \times 10^{-4}$	$(3.34 \pm 0.22) \times 10^{-4}$
$\Delta_0(B \to K^*\gamma)$	$(1.2 \pm 5.1) \times 10^{-2}$	$(5.33 \pm 2.6) \times 10^{-2}$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$(3.0 \pm 0.6 \pm 0.25) \times 10^{-9}$	$(3.54 \pm 0.27) \times 10^{-9}$
$\mathrm{BR}(B_u \to \tau\nu)$	$(1.06 \pm 0.19) \times 10^{-4}$	$(0.82 \pm 0.29) \times 10^{-4}$
$\mathrm{BR}(D_s \to \tau\nu)$	$(5.51 \pm 0.24) \times 10^{-2}$	$(5.13 \pm 0.11) \times 10^{-2}$
ΔM_{B_s}	17.76 ± 0.021 ps^{-1}	17.38 ± 1.505 ps^{-1}

Observable	Experiment	SM prediction
$\frac{\mathrm{BR}(B \to D\tau\nu)}{\mathrm{BR}(B \to D\ell\nu)}$	$0.403 \pm 0.040 \pm 0.024$	0.300 ± 0.012
$\frac{\mathrm{BR}(B \to D^*\tau\nu)}{\mathrm{BR}(B \to D^*\ell\nu)}$	$0.310 \pm 0.015 \pm 0.08$	0.248 ± 0.008

Assuming -23% experimental correlations between the two observables.

The experimental values and SM predictions for the observables related to $B \to K^{(*)}\ell^+\ell^-$ and $B_s \to \phi\mu^+\mu^-$ can be found in T. Hurth, F. Mahmoudi, and S. Neshatpour, Nucl. Phys. B909, 737 (2016), arXiv:1603.00865.

$$\delta C_9^{H^\pm(0)} = \frac{1-4s_W^2}{s_W^2}\,\mathcal{C}^{H^\pm(0)}(x_{tH^\pm}) - \mathcal{D}^{H^\pm(0)}(x_{tH^\pm})$$

$$\delta C_{10}^{H^\pm(0)} = -\frac{1}{s_W^2}\,\mathcal{C}^{H^\pm(0)}(x_{tH^\pm})$$

with $x_{tH^\pm} = \dfrac{m_t^2}{M_{H^\pm}^2}$ and

$$\mathcal{C}^{H^\pm(0)}(x) = \frac{M_{H^\pm}^2}{8M_W^2}\lambda_{tt}^2\,x^2\left\{\frac{-1}{(x-1)^2}\ln x + \frac{1}{x-1}\right\}$$

$$\mathcal{D}^{H^\pm(0)}(x) = \frac{1}{18}\lambda_{tt}^2\,x\left\{\frac{-3x^3+6x-4}{(x-1)^4}\ln x + \frac{47x^2-79x+38}{6(x-1)^3}\right\}$$

For $\delta C_{9,10}$ LO contributions proportional to λ_{tt}^2, i.e. $1/\tan^2\beta$ for all four types

Moreover, $\delta C_{9,10}^{H^\pm(0)}$ are both always of the same sign as $C_{9,10}^{\rm SM}$

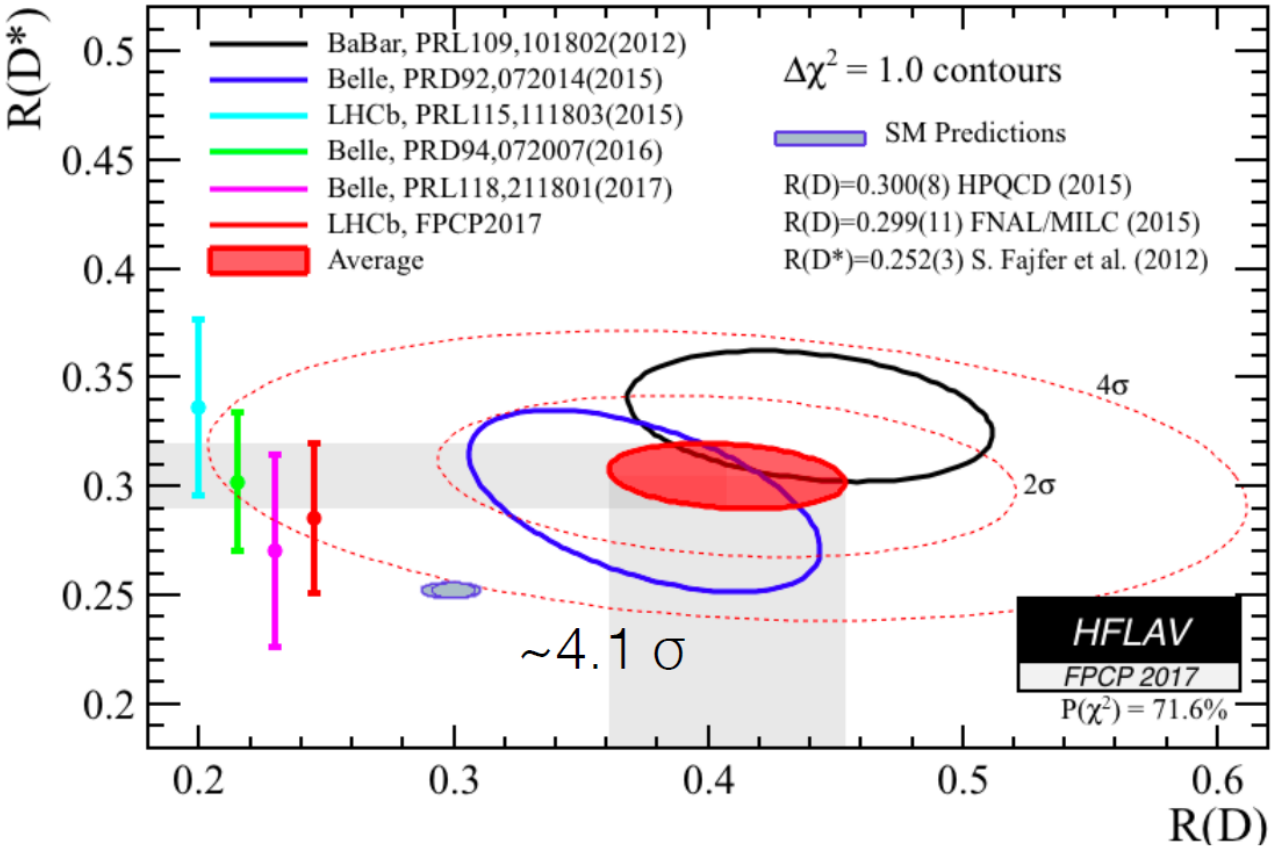
Experiment	R_{D^*}	R_D	Re-scaled Correlation
BaBar (2012) [3]	$0.332 \pm 0.024 \pm 0.018$	$0.440 \pm 0.058 \pm 0.042$	-0.27
Belle (2015) [4]	$0.293 \pm 0.038 \pm 0.015$	$0.375 \pm 0.064 \pm 0.026$	-0.49
LHCb (2015) [5]	$0.336 \pm 0.027 \pm 0.030$	–	–
Belle (2016) [6]	$0.302 \pm 0.030 \pm 0.011$	–	–
Belle (2017) [17]	$0.270 \pm 0.035^{+0.028}_{-0.025}$	–	–
LHCb (2017) [8]	$0.285 \pm 0.019 \pm 0.025\,(\text{syst}) \pm 0.013\ (\text{BF})$	–	–
Average	$0.304 \pm 0.013 \pm 0.007$	$0.407 \pm 0.039 \pm 0.024$	-0.20
SM [2, 18]	0.252 ± 0.003	0.299 ± 0.003	

LHCb 1708.08856: $R(D^*) = 0.285 \pm 0.019 \pm 0.025 \pm 0.013$

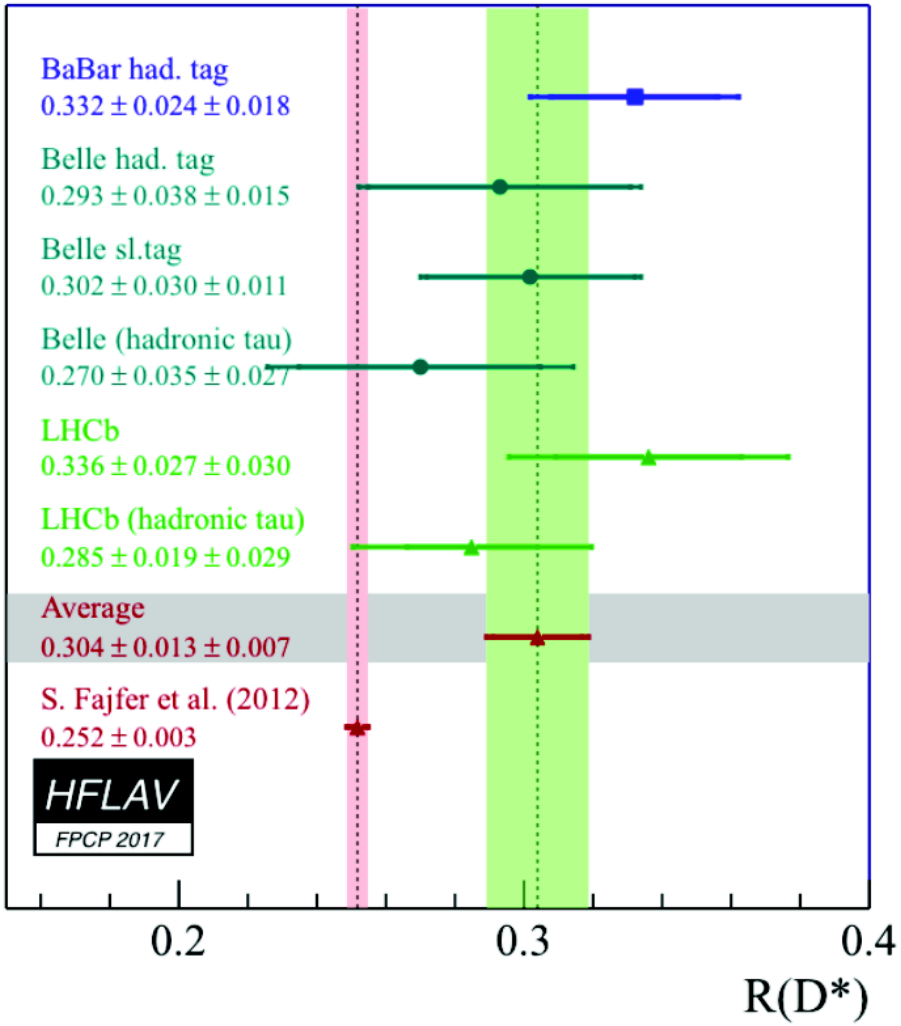
Belle 1709.00129: $R(D^*) = 0.270 \pm 0.035(stat)^{+0.028}_{-0.025}(syst)$

[17]: arXiv:1608.06391 ICHEP16

[8]: LHCb internal note


R(D*)
R(D)
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average
Δχ² = 1.0 contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
4σ
2σ
~4.1 σ
HFLAV
FPCP 2017
P(χ²) = 71.6%

$B \to D^{(*)}\ell\nu$


BaBar had. tag
0.332 ± 0.024 ± 0.018
Belle had. tag
0.293 ± 0.038 ± 0.015
Belle sl.tag
0.302 ± 0.030 ± 0.011
Belle (hadronic tau)
0.270 ± 0.035 ± 0.027
LHCb
0.336 ± 0.027 ± 0.030
LHCb (hadronic tau)
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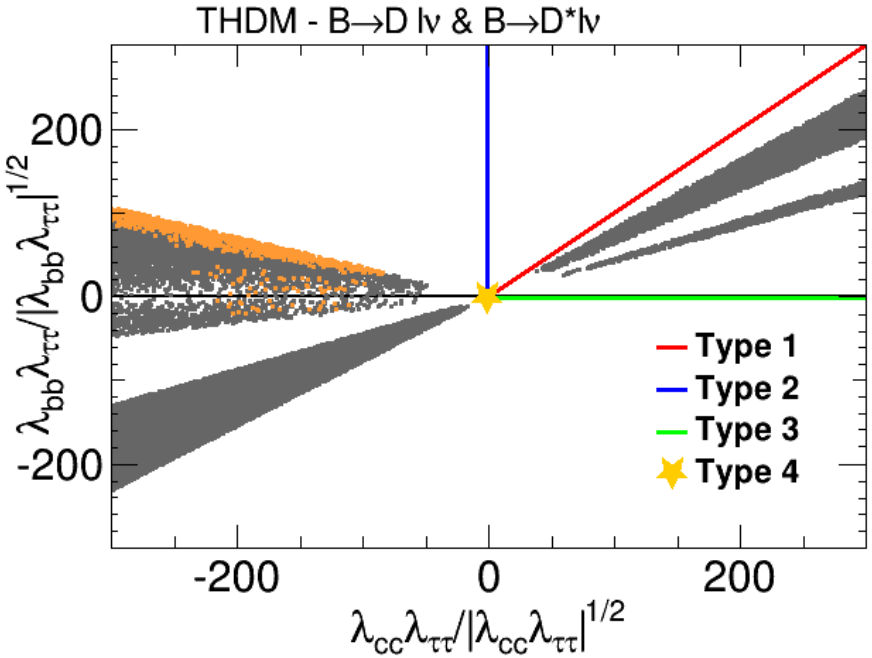
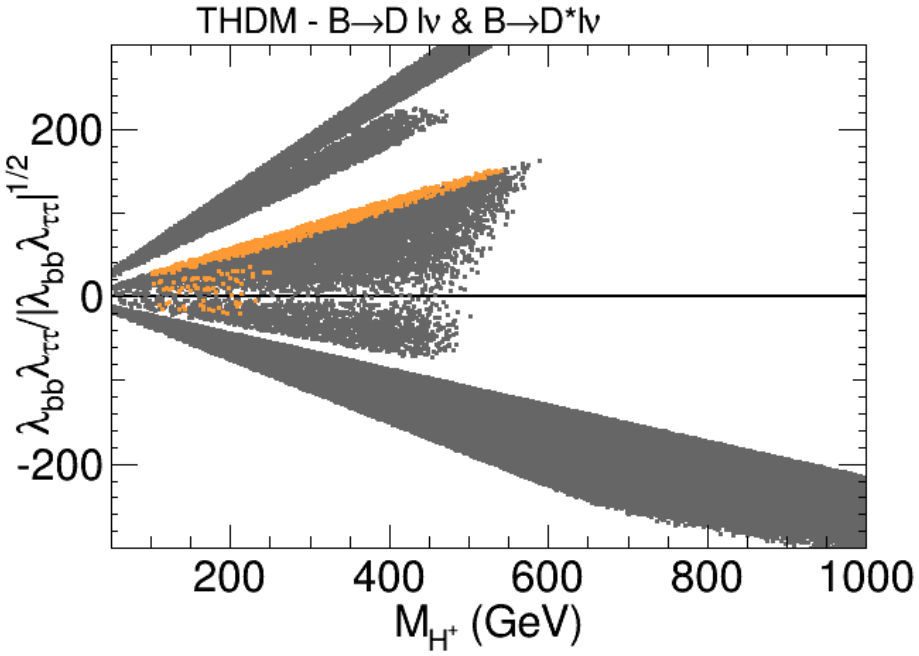
Average
0.304 ± 0.013 ± 0.007
S. Fajfer et al. (2012)
0.252 ± 0.003
HFLAV
FPCP 2017
0.2
0.3
0.4
R(D*)

Type	$\lambda_{cc}\lambda_{\tau\tau}/\sqrt{\lvert\lambda_{cc}\lambda_{\tau\tau}\rvert}$	$\lambda_{bb}\lambda_{\tau\tau}/\sqrt{\lvert\lambda_{bb}\lambda_{\tau\tau}\rvert}$
I	$\cot\beta$	$\cot\beta$
II	-1	$\tan\beta$
III	$\cot\beta$	-1
IV	-1	-1

Values of the parameters entering $B \to D^{(*)}\ell\nu$ observables for the different Z_2-symmetric Types

Considering generic couplings:





The grey points are in agreement with $B \to D^{(*)}\ell\nu$ constraints at 95% C.L., and the orange points are in addition in agreement with $\mathrm{BR}(B_u \to \tau\nu)$ and $\mathrm{BR}(D_s \to \tau\nu)$. The lines and star correspond to the regions accessible for the various Z_2-symmetric Yukawa types.